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STATISTICAL SUMMARY OF OCEANIC FRONTS AND WATER MASSES IN THE W--ETC(U)
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STATISTICAL SUMMARY OF OCEANIC FRONTS AND WATER MASSES IN THE WESTERN NORTH ATLANTIC

E. KHEDOURI
W. GEMMILL
M. SHANK

OCTOBER 1976

(Reprinted 1979)

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NAVAL OCEANOGRAPHIC OFFICE
NSTL STATION
BAY ST. LOUIS, MS. 39522

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ABSTRACT

Spatial variability and thermal characteristics of the Gulf Stream and the Slope Front are summarized to show the average or typical conditions. Thermally related parameters, such as sonic layer depths and sound channels, are summarized for each water mass separated by these fronts and subdivided by seasons. Results show that the thermal structure in the Gulf Stream region can be predicted, if the position of the Gulf Stream North Wall is known. In the absence of subsurface data, the North Wall position can be estimated better from the maximum surface temperature than from the maximum surface thermal gradient.

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FOREWORD

This report presents a detailed picture of two ocean fronts: the Slope Front bounding the waters of the Continental Shelf from Nantucket to Norfolk and the Gulf Stream system with emphasis on the sharply defined North Wall.

Extensive thermal structure data acquired by repeated ship bathythermograph surveys between New York and Bermuda and numerous aerial surveys using airborne radiation sensing and air-droppable bathythermographs were used as a basis for the statistical summaries. This work is a response to requirements by COMSIXTHFLT and CINCLANTFLT for improved knowledge of ocean fronts, ultimately leading to a capability to predict frontal characteristics and their impact on ASW operations.

J. E. AYRES
Captain, USN
Commander

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TABLES

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I. INTRODUCTION

An oceanic front is the interface between water masses of different physical characteristics; it is similar to a weather front because of strong density gradients across the front and a systemized circulation with instability perturbations along the front. Two important fronts are found within the western North Atlantic Ocean; the Slope Front between the Shelf Water and Slope Water, and the Gulf Stream North Wall between the Gulf Stream and Slope Water. Figure 1 shows a typical position of these fronts based on an infrared satellite photograph. Another front occurs at the southern edge of the Gulf Stream separating the Gulf Stream from the Sargasso Sea. This front is insignificant because the thermal gradients are very weak and its surface location is usually undetectable.

Anomalies in sound velocity patterns are produced by complex density fields associated with strong fronts, and the result is extreme variability in active and passive sonar ranges. The objective of this paper is to describe the location, variability, and thermal characteristics of fronts located off the east coast of the United States. The data base (except where otherwise indicated) consists of 66 bathythermograph surveys along a line between New York and Bermuda. The surveys were conducted approximately once a week from April to November 1970 and April to September 1971.

II. GENERAL THERMAL CHARACTERISTICS

Thermal gradients across oceanic fronts are determined by the temperatures of the water masses which the fronts separate. Typical temperature profiles for various water masses and for each season are shown in figure 2. Oceanic seasons in this region lag atmospheric seasons, and transitional periods (spring and autumn) are shorter in the ocean. The oceanic seasons used in this publication are defined as follows:

Spring - May-June	Summer - July-September
Autumn - October-December	Winter - January-April

A. Slope Front

The Slope Front is a boundary between Shelf and Slope Waters. In winter the Slope Front is easily identified by a surface temperature difference of approximately 7°C between Slope Water and Shelf Water. This is not true in summer because surface heating produces fairly uniform surface temperatures across both water masses. Often colder Shelf Water overrides warmer Slope Water resulting in temperature inversions along this front. These inversions are dynamically stable because Shelf Water is less saline than the Slope Water. At a depth of 50 m Shelf Water is considerably colder than Slope Water and this temperature gradient can sometimes be used to identify the front. The Slope Front is shallow and thus very susceptible to air-sea interactions, mixing, and advection. These processes may make location of the front difficult.

B. North Wall

The North Wall separates the Gulf Stream from Slope Water. There is usually a surface temperature difference of 3°-7°C between the two water masses. As with the Slope Front, the temperature difference is greater in winter than in summer. Based on many observations a strong temperature gradient always occurs at a depth of 200 m, where the temperature at the center of the gradient zone is approximately 15°C. Because of this, it is common practice to identify the North Wall position by the 15°C isotherm at 200 m. This method of Gulf Stream tracking was reported by Fuglister and Voorhis (1965). Gulf Stream Water, being lighter than Slope Water, overrides the Slope Water to a varying degree depending upon meandering of the stream and the nature of outside forces. Consequently, the location of the maximum surface temperature gradient (the surface front) is to the left of the subsurface front when one looks downstream.

III. VERTICAL CROSS SECTIONS OF FRONTS

Figure 3 shows a typical winter thermal cross section between New York and Bermuda. The main feature of this section is a strong horizontal temperature gradient formed by the North Wall at 36°55'N. Two secondary features are the horizontal gradients formed by the southern edge of the stream at 36°30'N, and the Slope Front. The Gulf Stream can be identified at the surface as warm water (>19°C) bounded by Sargasso Water (18°C) to the south and Slope Water (15°-19°C) to the north. Because of these strong gradients, the width of the stream can be calculated in winter from temperature data. The surface width varies from 50 to 100 km at this latitude. The Slope Front can be identified by a temperature change of approximately 2°C near the Continental Shelf.

Figure 4 shows a typical summer thermal section between New York and Bermuda. The dominant feature is the strong horizontal temperature gradient across the North Wall at 37°40'N at a depth of 200 m. In contrast to the winter section, the near-surface horizontal temperature gradients are weak for all water mass boundaries during summer. Thus the Slope Front and the southern edge of the Gulf Stream cannot usually be identified by surface temperature horizontal gradients.

IV. SONIC LAYER DEPTHS, IN-LAYER AND BELOW-LAYER GRADIENTS

Mean values and standard deviations of several parameters of importance to ASW, which were calculated from temperature data between New York and Bermuda, are summarized in table 1. These include: (1) sonic layer depth (SLD), defined as the depth of the

TABLE 1

SEASONAL CHARACTERISTICS OF WATER MASSES

		SST (°C)			SLD (m)			ILG (°C/10m)			BLG (°C/10m)		
		#Obs	Mean	S.D.	#Obs	Mean	S.D.	#Obs	Mean	S.D.	#Obs	Mean	S.D.
Winter Jan-Apr	Sargasso	152	19.6	1.5	133	322.7	220.6	152	-.01	.03	146	-.19	.15
	Gulf Stream	119	20.2	3.9	119	88.9	92.3	119	.02	.06	119	-.39	.29
	Slope	89	14.8	2.6	89	71.3	71.7	89	.00	.05	89	-.58	.50
	Shelf	87	8.0	2.1	87	142.6*	40.4*	86	-.32*	.13*	87	-.24*	.14*
Spring May-Jun	Sargasso	298	22.6	1.8	236	87.6	163.0	298	.01	.05	295	-.43	.27
	Gulf Stream	237	23.6	2.9	237	30.1	24.2	237	.05	.18	237	-.75	.65
	Slope	331	17.3	3.6	331	23.5	40.4	331	.05	.15	331	-1.13	.93
	Shelf	99	12.6	2.5	99	107.9*	28.1*	94	.33*	.31*	99	-.45*	.53*
Summer Jul-Sep	Sargasso	403	26.5	1.3	402	22.0	21.5	403	-.01	.06	402	-.62	.42
	Gulf Stream	521	27.2	1.2	521	22.8	20.8	521	.01	.17	521	-.84	.63
	Slope	625	23.7	2.7	625	9.2	10.8	625	.04	.18	625	-2.35	1.12
	Shelf	52	23.4	2.0	52	20.3	5.7	52	.95	.39	52	-3.00	1.09
Autumn Oct-Dec	Sargasso	70	24.4	1.1	70	65.8	30.5	70	-.02	.03	70	-.64	.38
	Gulf Stream	134	24.7	1.9	134	65.8	26.3	134	-.01	.05	134	-1.07	.83
	Slope	88	20.4	2.8	88	29.8	16.0	88	.06	.18	88	[illegible]	.99
	Shelf	17	21.6	1.8	17	31.4	7.3	17	-.07	.28	17	-2.45	.92

* Values of SLD, BLG, and ILG may be restricted by depth of bottom.

SST Sea surface temperature
SLD Sonic Layer Depth
ILG In-layer vertical gradient
BLG Below-layer vertical gradient

S.D. Standard Deviation

sound velocity maximum in the upper ocean; (2) in-layer gradient (ILG), defined as the vertical temperature gradient (°C/10 m) between the surface and the SLD; and (3) below-layer gradient (BLG), which is the vertical temperature gradient (°C/10 m) between the SLD and 30 m below the SLD.

As an example of the variability across the fronts, table 2 shows the average change in each of the above parameters for a northbound transit of the North Wall and Slope Front in each season. In winter for example, a northbound ship will encounter the following changes. The surface temperature will decrease by approximately 5.4°C, from 20.2°C to 14.8°C as the North Wall is crossed. The SLD may change from 90 to 70 m, and the ILG and BLG may decrease by 0.02°C/10 m and 0.19°C/10 m, respectively. When the Slope Front is crossed, there will be a further reduction of SST of 6.8°C. The SLD, however, will increase by 70 m and the ILG and BLG will increase by 0.3°C/10 m. Note that the ratio of standard deviations to the mean values is large in table 1 for all the parameters except the SST. Therefore the changes shown in table 2 will not occur on every transit and cannot be used for identifying the water masses.

TABLE 2
Change in Water Mass Characteristics
Encountered on Northbound Crossings of the Fronts

	North Wall				Slope Front			
	SST°C	SLD(m)	ILG °C/10m	BLG °C/10m	SST°C	SLD(m)	ILG °C/10m	BLG °C/10m
Winter	-5.4	-17.6	- .02	- .19	-6.8	71.3*	-.32*	+.34*
Spring	-6.3	- 6.6	0.0	- .38	-4.7	84.4*	+.28*	+.68*
Summer	-3.5	-13.3	+ .04	-1.51	- .3	11.1	+.91	-.69
Autumn	-4.3	-36.0	+ .64	- .64	1.2	1.6	-.13	-.74

*May be restricted by depth of bottom

V. SOUND CHANNELS

Changes in the deep sound channel in the Gulf Stream region are significant. The deep sound channel axis is deepest in the Sargasso Sea with a mean depth near 1,250 m and an average minimum sound velocity of 1,492 m/s. In the Gulf Stream the axis is approximately 900 m deep and the average minimum sound velocity is 1,486 m/s. In Slope Water the axis is shallowest at about 700 m and has an average sound velocity of 1,480 m/s.

Near-surface sound channels also occur in this region. These are less important to sound propagation than the deep sound channels, particularly at low frequencies. Their presence or absence, however, can alter typical sound paths for a particular water mass. The two most common types of near-surface channels in this region are (1) sound channels formed by mixing of different water masses and (2) sound channels formed by water mass thermohaline structure. The first type occurs along the North Wall and the Slope Front and is easily identified from bathythermograms as a temperature inversion. It is usually of small scale and tends to be transient and therefore not predictable. The second type occurs within Shelf and Sargasso Waters. This type of channel is persistent, and is therefore more important in ASW.

Examples of the two types of near-surface sound channels are shown in figure 5. The first profile (5a) is typical for Sargasso Water during spring. Surface heating has produced a negative gradient near the surface. The sound channel axis occurs at 90 m and extends from the surface to 450 m. Because of its depth, thickness, and persistence, the sound channel is important in trapping sound near the surface. The second profile (5b) observed between the Gulf Stream and Slope Water shows a strong sound channel formed by mixing of the two water masses. It extends from 55 to 200 m with axial depth at 70 m. This type of transient sound channel is common near the Gulf Stream and is frequently responsible for anomalous sound propagation. Table 3 summarizes the upper sound channel axis depth (AXD), thickness (THK), degrees trapped (DEGT), sound channel strength (SCS), and frequency of occurrence for each season and water mass within the study area. The sound channel strength is computed by:

$$SCS = \frac{THK\ (m)}{DEGT} \times 30.48$$

On the basis of these calculations, sound channels in the Sargasso Sea are the strongest. Details for sound channel analysis have been reported by Anderson (1967).

VI. ENTRAINMENT

A feature often observed in detailed surveys of the North Wall using airborne radiation thermometer is a long filament of cold water on the shoreward side of the Gulf Stream (Fisher and Gotthardt, 1970). This feature was observed in 7 out of 12 surveys made between 9 October 1968 and 16 May 1969 survey.

TABLE 3

SUMMARY OF SPECIFIC SOUND CHANNEL PROPERTIES WITHIN WATER MASSES

			AXD (m)		THK (m)		DEGT		SCS		
		#Obs	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	*Freq.Occ.%
Winter Jan-Apr	Sargasso	79	172.0	63.1	335.4	101.5	3.3	.6	36.9	15.1	52
	Gulf Stream	50	176.1	92.0	125.2	87.8	4.4	1.7	17.4	11.3	46
	Slope	80	148.8	163.3	119.6	90.0	4.1	1.5	14.4	8.5	91
	Shelf	30	305.2	227.0	194.0	128.9	3.2	.7	19.2	13.5	37
Spring May-Jun	Sargasso	245	190.9	68.9	419.0	81.6	3.5	.6	47.9	14.0	80
	Gulf Stream	134	142.7	97.1	123.1	97.9	5.2	1.9	19.5	14.4	53
	Slope	439	182.4	206.6	148.4	127.6	4.6	1.8	19.4	13.1	100
	Shelf	141	135.3	190.4	104.0	108.9	5.3	1.8	14.2	10.2	100
Summer Jul-Sep	Sargasso	222	225.5	52.1	394.1	57.5	3.4	.6	41.2	9.1	68
	Gulf Stream	104	168.8	84.0	133.0	125.2	4.9	2.1	15.8	10.7	22
	Slope	629	248.4	226.7	178.1	141.9	4.4	1.9	20.6	13.7	93
	Shelf	60	209.5	213.2	136.6	131.4	4.9	2.0	15.8	11.8	95
Autumn Oct-Dec	Sargasso	37	245.6	49.8	327.2	66.6	2.9	.2	31.3	8.2	30
	Gulf Stream	38	156.0	52.5	126.4	94.3	4.3	1.9	14.8	8.2	17
	Slope	72	213.6	213.2	124.3	124.7	5.1	2.1	15.0	10.8	63
	Shelf	11	106.3	106.3	50.9	60.4	5.7	2.1	9.4	6.8	100

*Includes multiple sound channels

AXD Axial Depth
THK Sound Channel Thickness
DEGT Degrees Trapped
SCS Sound Channel Strength

Poorly defined cold filaments were observed on two flights and none on three flights. A typical entrained cold filament observed during the 12 May 1969 survey is shown in figure 6. The intrusion of a cold-water tongue approximately 2 km in width was observed during this survey parallel to the northern edge of the Gulf Stream for a distance of more than 100 km. The thermohaline structure of this filament indicates that it is of Shelf Water origin entrained by eastward movement of the Gulf Stream. Owing to formation of long, narrow sound channels within the entrainment, this feature may be of significant operational importance.

VII. NORTH WALL THERMAL STABILITY

Figure 7 shows the mean thermal structure relative to the North Wall (15°C at 200 m) based on 66 transits of the frontal zone. Stability of this pattern is indicated by low standard deviations in table 4. These were computed at 20 m depth intervals for every 5 minutes of latitude along the ship's track for a distance of 60 km from the North Wall. Below 200 m there is very little change in temperature during the year. For instance, at the North Wall (distance equals zero) at a depth of 300 m the standard deviation is 1.0°C. This means, assuming a normal distribution of the data, that 95 percent of the temperatures fall within $\pm$ 2.0°C of the mean value shown in figure 7.

The thermal variability shown in table 4 is an indicator of the thermal pattern consistency of figure 7, since the standard deviations are calculated relative to distance from the North Wall for each cross section. Much larger deviations are found if the computations are based on distance from a mean geographical position of the North Wall. This would represent variances caused by lateral movement of the stream as well as seasonal variations and observational errors.

Figure 8 presents mean seasonal diagnostic models for the Gulf Stream thermal structure. On the basis of these cross sections, one can estimate the relative thermal structure within 60 km of the North Wall. If a recent bathythermogram is available, the thermal structure can be reconstructed by adjusting the isotherm values. Table 5 presents temperature standard deviations relative to the position of the North Wall in the upper 200 m for each temperature pattern shown in figure 8.

VIII. MOVEMENT OF FRONTS

Movement of the North Wall has two major components, displacement of the axis north or south of its mean position and wavelike perturbations that move along the front. These latter movements are meanders and are the most common cause of changes in the position of the North Wall. The limits of North Wall movements shown by figure 9 are based on 85 aerial surveys using an airborne

TABLE 4

Temperature Standard Deviations (°C) Relative to the North Wall

Depth (m)												
0	4.5	4.5	4.4	4.5	4.1	3.5	2.6	2.1	2.4	2.2	2.5	2.5
	4.5	4.4	4.4	4.9	4.4	4.1	2.5	2.1	2.4	2.2	2.4	2.5
	2.8	3.0	2.8	3.5	3.8	4.2	2.4	2.0	2.4	2.2	2.4	2.5
	1.6	1.9	2.0	2.1	3.2	4.0	2.2	1.8	2.2	2.1	2.2	2.2
100	1.0	1.3	1.4	1.5	2.7	3.9	1.9	1.7	2.0	1.9	1.9	1.9
	.7	.8	1.0	1.3	2.2	3.4	1.9	1.6	1.8	1.6	1.6	1.5
	.5	.6	.7	1.0	1.5	2.7	1.8	1.4	1.6	1.4	1.3	1.2
	.8	.7	.7	.8	1.2	2.0	1.8	1.2	1.4	1.1	1.0	.9
	.9	.9	.8	.8	1.0	1.9	1.7	1.1	1.2	.9	.8	.7
200	1.0	1.0	.9	1.0	1.0	1.4	1.6	1.1	1.0	.6	.5	.5
	1.1	1.1	1.0	1.3	1.0	1.0	1.5	1.0	.9	.5	.3	.3
	1.1	1.1	1.0	1.1	1.0	.8	1.5	.9	.9	.4	.3	.3
	1.1	1.1	1.0	1.1	1.1	.9	1.5	.9	.9	.3	.2	.2
	1.1	1.1	1.0	1.1	1.2	.8	1.6	.9	.9	.3	.2	.2
300	1.1	1.1	1.0	1.1	1.2	1.0	1.7	1.1	.9	.3	.2	.2
	1.0	1.0	.9	1.0	1.2	1.0	1.7	1.2	.9	.3	.2	.2
	1.0	1.0	.9	1.0	1.2	1.1	1.7	1.3	1.0	.4	.2	.2
	.9	.9	.9	1.0	1.2	1.1	1.7	1.5	1.1	.4	.2	.2
	.8	.9	.8	1.0	1.2	1.1	1.7	1.6	1.2	.4	.2	.2
400	.8	.8	.8	1.0	1.1	1.2	1.8	1.7	1.3	.5	.2	.2
	.7	.7	.8	.9	1.1	1.1	1.8	1.8	1.4	.6	.3	.2
	.6	.7	.7	.8	1.1	1.1	1.8	1.9	1.5	.7	.3	.3
	.6	.6	.6	.8	1.0	1.1	1.8	2.0	1.6	.8	.4	.3
	.5	.5	.6	.7	.9	1.0	1.7	2.0	1.8	1.0	.5	.4
500	.4	.5	.5	.6	.9	1.0	1.6	2.0	1.9	1.1	.7	.5
	.4	.4	.5	.6	.8	1.0	1.5	2.0	1.9	1.3	.9	.6
	.3	.4	.4	.5	.7	.9	1.4	2.0	2.0	1.4	1.0	.7
	.3	.3	.4	.5	.7	.9	1.5	2.0	2.1	1.6	1.1	.8
	.3	.3	.3	.5	.6	.9	1.4	1.9	2.1	1.7	1.3	1.1
600	.3	.3	.3	.5	.6	.8	1.3	1.8	2.1	1.7	1.4	1.2
	.3	.3	.3	.4	.6	.7	1.3	1.7	2.0	1.7	1.5	1.3
	.3	.3	.3	.4	.6	.7	1.2	1.6	2.0	1.8	1.5	1.3
	.3	.3	.3	.4	.5	.7	1.2	1.7	2.0	1.8	1.6	1.4
	.3	.3	.3	.4	.5	.7	1.2	1.6	2.0	1.8	1.6	1.5
	.3	.3	.3	.4	.5	.7	1.1	1.6	2.1	1.8	1.7	1.5
700	.3	.3	.3	.4	.6	.7	1.1	1.6	2.1	1.7	1.7	1.7

60 40 20 0 20 40 60

North South

Distance From North Wall (km)

TABLE 5

Seasonal Temperature Standard Deviations Relative to the North Wall

Spring

Depth (m)												
0 --	3.3	3.8	3.0	3.4	3.1	2.7	1.7	1.1	1.8	1.1	1.3	1.3
	3.2	3.7	3.2	3.8	3.6	4.0	1.6	1.1	1.8	1.1	1.3	1.4
	2.8	3.3	2.9	3.2	3.2	4.0	1.3	1.1	1.9	1.3	1.4	1.4
	1.7	2.1	2.3	2.4	3.1	3.8	1.6	1.5	2.2	1.4	1.3	1.4
100 --	1.1	1.8	1.7	1.9	2.5	4.4	1.8	1.5	2.0	1.4	1.2	1.4
	.8	1.1	.9	1.6	2.3	3.7	1.7	1.3	1.7	1.3	1.1	1.3
	.5	.8	.6	1.1	1.6	2.5	1.6	1.1	1.6	1.1	1.0	1.1
	.6	.4	.6	.7	1.0	2.3	1.7	1.0	1.4	.9	.9	.8
	.5	.5	.9	.7	.7	2.0	1.7	1.0	1.3	.7	.7	.7
200 --	.7	.6	.9	.9	.6	1.4	1.5	.8	1.1	.5	.6	.6
	.9	.8	1.1	1.0	.5	1.0	1.5	.8	1.1	.4	.4	.5

Summer

Depth (m)												
0 --	2.0	2.2	2.1	2.1	2.2	1.7	.9	.9	.9	1.0	1.1	1.1
	2.8	2.8	2.4	2.4	2.2	1.4	.9	.9	.8	1.0	1.1	1.1
	2.4	2.5	2.7	3.1	3.3	2.7	1.9	1.5	1.3	1.2	1.4	1.5
	1.1	1.6	1.7	2.4	3.3	3.4	2.2	1.7	1.5	1.5	1.7	1.8
	.8	1.0	1.0	1.5	2.8	3.2	2.0	1.8	1.6	1.6	1.7	1.7
100 --	.5	.7	.9	.9	1.9	2.7	2.2	1.8	1.6	1.6	1.6	1.4
	.6	.6	.6	.7	1.4	2.5	2.0	1.6	1.4	1.4	1.3	1.0
	.7	.7	.7	.7	1.1	1.7	2.1	1.4	1.3	1.1	1.0	.8
	.8	.8	.7	.6	1.0	1.5	1.8	1.3	1.1	.9	.8	.6
200 --	.8	.8	.7	.7	1.0	1.2	1.5	1.5	.9	.7	.6	.4
	.8	.9	.8	.7	1.0	1.0	1.4	1.7	.8	.6	.4	.4

Autumn

Depth (m)												
0 --	1.6	1.8	1.8	2.6	2.0	1.3	1.1	1.0	.7	.8	.8	.8
	1.9	1.7	2.1	2.7	2.2	1.4	1.1	1.0	.7	.8	.8	.8
	2.4	1.4	3.7	3.5	2.7	3.2	1.1	1.1	.7	.8	.7	.7
	1.1	1.1	1.9	3.4	2.7	3.1	2.0	.7	.8	.8	.5	.4
	.4	.6	.7	.7	3.6	2.7	1.8	.4	1.5	1.2	.8	.9
100 --	.3	.4	.5	.6	3.2	3.8	2.2	1.0	1.8	1.6	1.3	1.4
	.5	.5	.4	.5	.9	3.3	1.6	1.3	1.6	1.5	1.3	1.2
	.9	.8	.4	.4	.6	1.4	1.8	1.0	1.3	1.3	1.2	1.1
	.9	.8	.4	.3	.7	1.3	1.2	1.0	1.0	1.0	1.1	1.0
200 --	1.1	.9	.5	.3	.7	.7	1.1	.8	.7	.7	.7	.8
	1.1	1.0	.4	.3	.7	.6	1.2	.9	.5	.5	.5	.6

Winter

Depth (m)												
0 --	2.8	2.8	3.1	3.6	2.8	3.0	1.9	1.0	1.1	1.0	1.5	1.6
	2.5	2.7	3.1	3.4	2.8	2.9	1.9	1.0	1.1	1.1	1.5	1.7
	2.1	2.7	2.0	3.1	2.7	2.8	1.9	1.0	1.1	1.2	1.5	1.6
	1.0	2.2	2.2	2.1	2.7	2.6	1.7	.7	1.1	1.3	1.5	1.3
	.8	1.4	.7	1.4	2.1	2.4	1.5	.6	1.1	1.3	1.2	1.2
100 --	.7	1.3	.8	1.3	2.1	2.4	1.5	.7	1.3	1.1	1.2	1.1
	.4	.9	.9	1.4	1.8	2.1	1.4	.9	1.2	1.2	.9	1.0
	.6	.7	.8	1.3	1.6	1.8	1.5	1.0	1.0	1.1	.7	.8
	.8	.7	.8	1.2	1.2	1.7	1.5	1.0	1.0	1.0	.7	.8
200 --	.9	.8	.9	1.4	1.1	1.3	1.4	1.0	.9	.8	.7	.7
	1.1	.9	1.0	2.1	1.4	1.0	1.3	.9	.9	.8	.5	.6

60 40 20 0 20 40 60

North South

Distance from North Wall (km)

radiation thermometer. Maximum observed deviation from the mean path and the 95-percent probability boundary are shown.

Gulf Stream meanders are typically 200 to 400 km in length, move at a phase speed of 5 to 10 cm/s, and increase in amplitude as they proceed eastward from Cape Hatteras. During meandering the stream is displaced at the surface and at depth. During an anticyclonic bend of the meander, the surface water overrun results in greater mean separation between the surface front and the 200 m positions of the North Wall than during a cyclonic bend as described by Hansen and Maul (1970). Thus the temperature cross sections of an anticyclonic bend will show a greater slope of iostherms near the surface than a cross section of a cyclonic bend.

The mean position of the Slope Front and the limits of its movement based on 15 aircraft surveys are shown in figure 10. Available data indicate that the shoreward limit of the Slope Front closely follows the 100-fm (183 m) isobath and the outer limit overlaps the western boundary of the North Wall limits. Accordingly, it is possible for Shelf Water to form a boundary with Gulf Stream Water. This situation is usually characterized by very strong surface temperature gradients (10°C/km) and occurs close to Cape Hatteras.

Meander movement of the Slope Front and the North Wall is illustrated by figure 11 (U.S. Naval Oceanographic Office, Feb 1971). The two positions were observed 7 days apart during aerial surveys of February-March 1971. Movement of the meanders was in opposite directions, the Gulf Stream meander moved northeastward with propagation speed of 10 cm/s and the Slope Front meander moved southwestward at 7.5 cm/s. Both meanders moved downstream in the direction of the general flow.

Another series of observations of these fronts was made during 66 transits between New York and Bermuda by RMS FRANCONIA in 1970 and 1971. Mean positions of the two fronts based on these crossings are shown in figure 12 (U.S. Naval Oceanographic Office, Dec 1971). Although the North Wall moved over a lateral distance of 166 km during the 2-year period, 95 percent of the time the lateral movement was confined within 95 km.

IX. SURFACE AND SUBSURFACE POSITIONS OF NORTH WALL

Sea surface temperature data are generally more readily available than subsurface data. Many naval applications, however, require knowledge of conditions below the thin surface layer. Consequently, the relationship of surface thermal characteristics to the position of the subsurface front is important. A study by Hansen and Maul (1970) based on 100 transects of the stream revealed that the North Wall at 200 m occurs about 14.5 km to the warm side of the surface front with no apparent seasonal or geographical effects on this mean displacement.

The relationship of the surface front and maximum surface temperature to the North Wall (15°C at 200 m) was investigated with RMS FRANCONIA cross sections between New York and Bermuda. The locations of the North Wall, the surface front, and the maximum surface temperature for 1970 and 1971 RMS FRANCONIA cross sections are shown in figure 13 (U.S. Naval Oceanographic Office, Feb 1972). The mean absolute horizontal distance between the North Wall and the above two parameters cannot be calculated from FRANCONIA data, since the angle of crossings of the path of the Stream on each particular survey is not known and, therefore, the distance cannot be normalized. Comparison of displacement of the surface front and maximum surface temperature from the North Wall, however, can be made because both are increased proportionally by any deviation of the crossing angle from the normal. Table 6 lists the mean difference, the standard deviation, and the range of displacement from the North Wall for the surface front and the maximum surface temperature. These results show that the maximum surface temperature is a better indicator of the North Wall position than is the surface front.

TABLE 6
Comparison of Positions of Maximum Surface Temperature and the Surface Front to the Deep Front (15°C at 200 m)

	Maximum Surface Gradient	Maximum Surface Temperature
Number of crossings	66	66
Mean difference (km)	59.3	20.6
Standard deviation (km)	112.3	24.0
Maximum value (km)	319.7 (north)	128.5 (north)
Minimum value (km)	-225.5 (south)	-16.1 (south)
Range (km)	545.2	144.6

X. SUMMARY AND CONCLUSIONS

The North Wall of the Gulf Stream and Slope Front are the two most dominant thermal features within the western North Atlantic. A ship crossing these fronts will experience changes in temperature, sonic layer depth, in-layer gradient, below-layer gradient, and sound channel properties. These changes are summarized in tables 1 through 3.

The Gulf Stream has a relatively stable thermal structure if described relative to the position of the North Wall and if data are subdivided by seasons. If the position of the North Wall is known, seasonal models (fig. 8) can be used to predict the thermal structure with the accuracy indicated by standard deviations in table 5.

The position of the North Wall along a line between New York and Bermuda has varied 166 km during 2 years of observation. Ninety-five percent of the time, however, the lateral movement was confined within 95 km. The most common cause of this movement was meandering.

In the absence of subsurface temperature data, the position of the North Wall can be estimated from either the surface front or the maximum surface temperature. Maximum surface temperature is a better indicator of the North Wall position than is the surface front (area of maximum horizontal thermal gradient).

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U.S. Naval Oceanographic Office, The Gulf Stream Summary, 6 (12), December 1971.

U.S. Naval Oceanographic Office, The Gulf Stream Summary, 7 (2), February 1972.

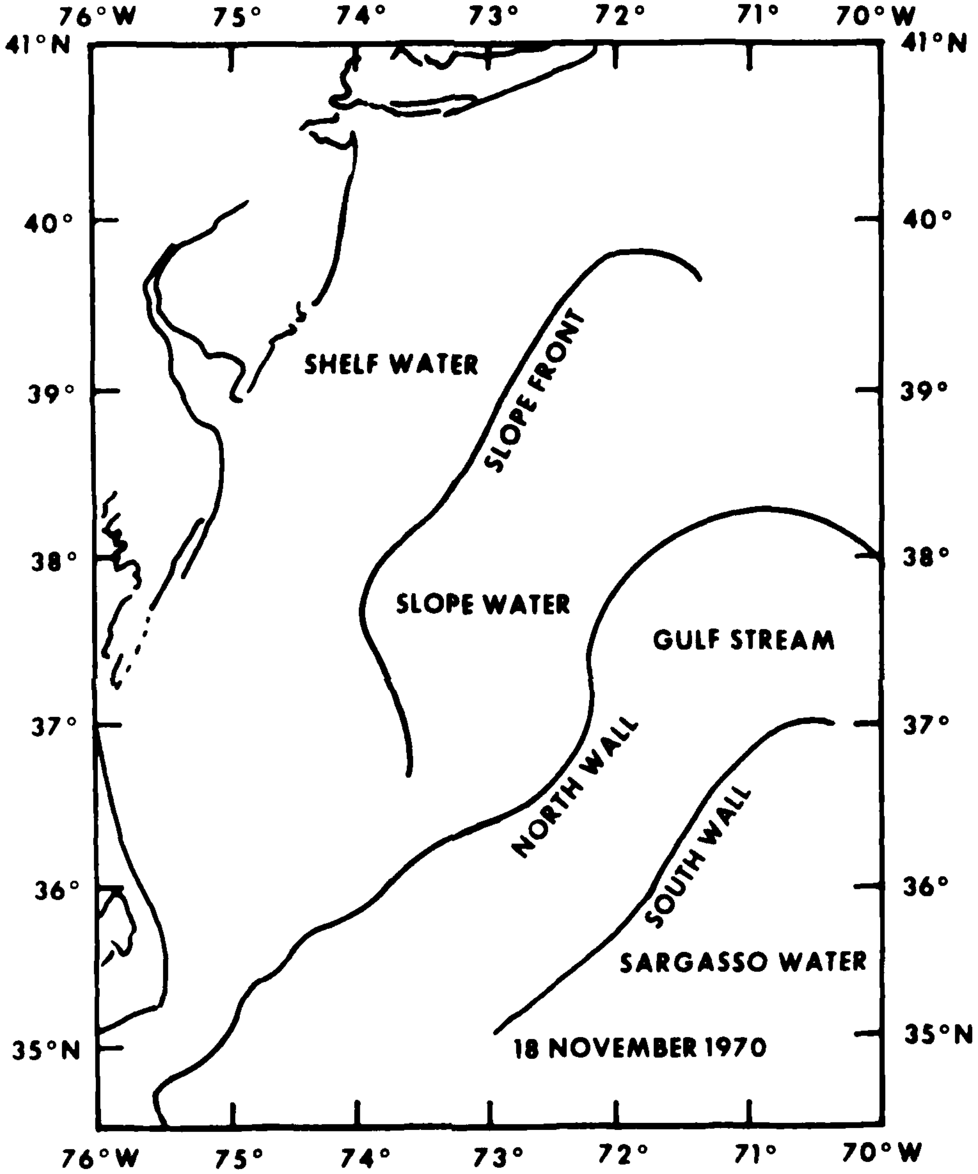


Figure 1 - Frontal Positions Based on Infrared Satellite Photograph

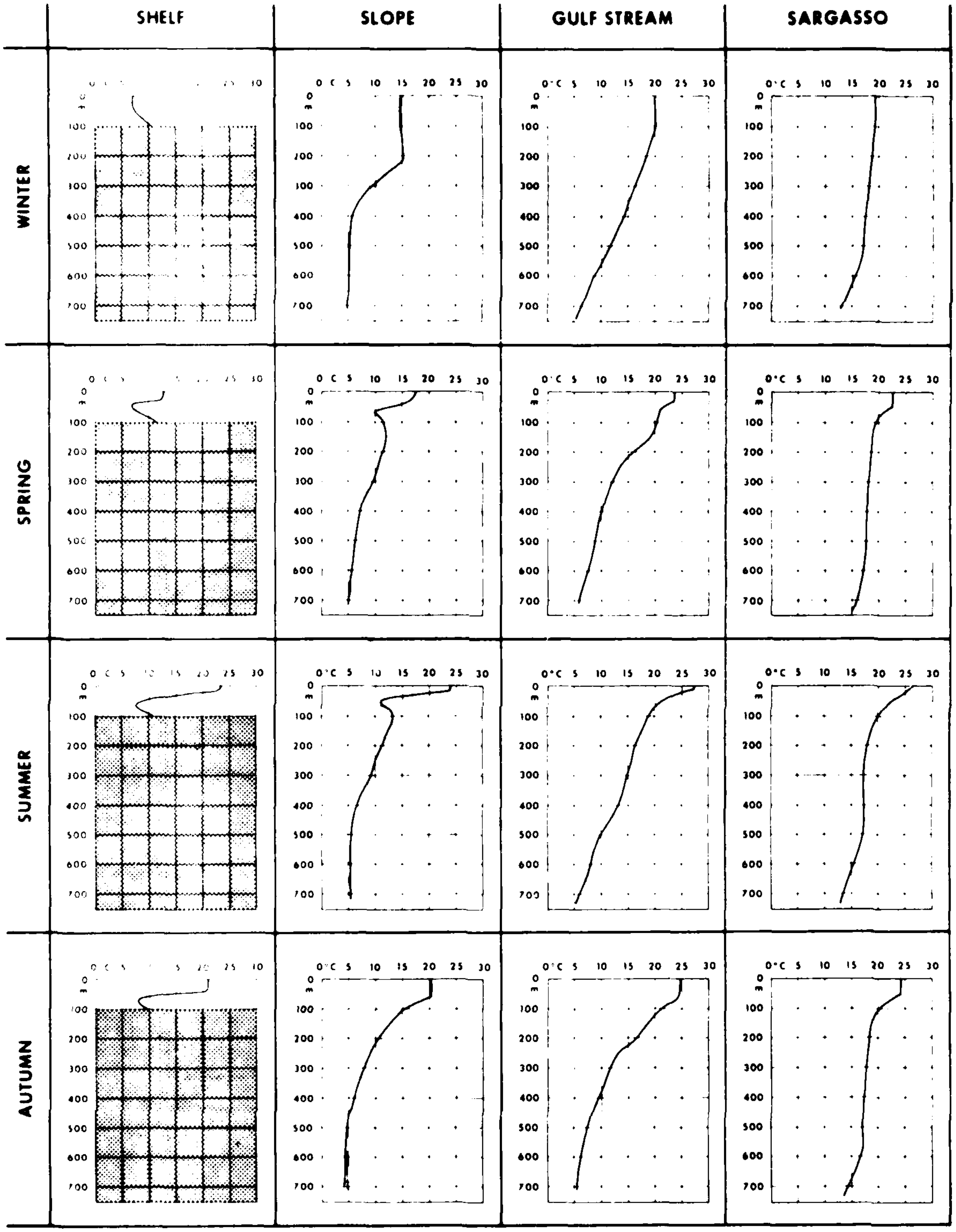


Figure 2 - Representative Bathythermograms

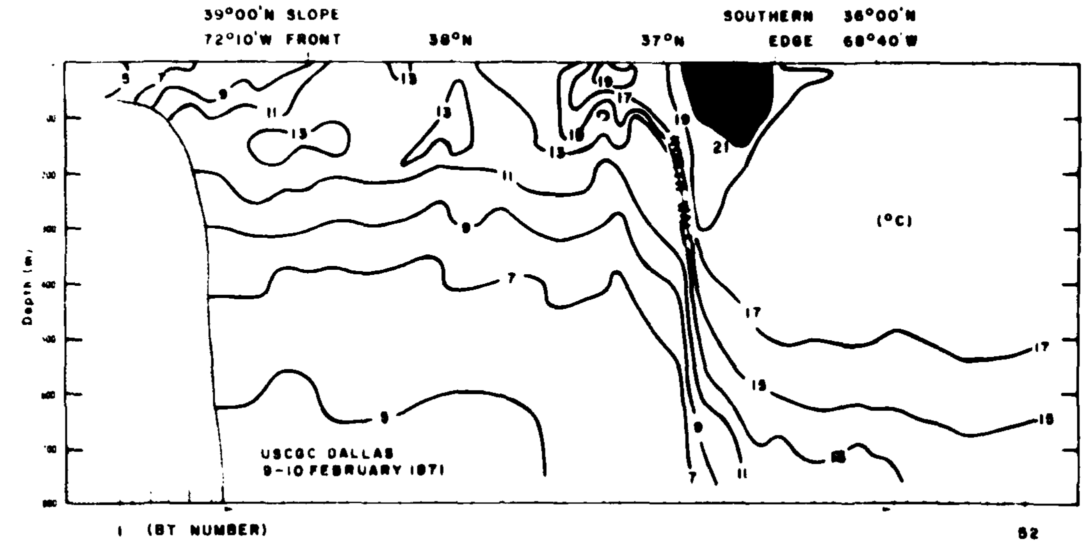


Figure 3 - Typical Winter Temperature Cross Section Between New York and Bermuda

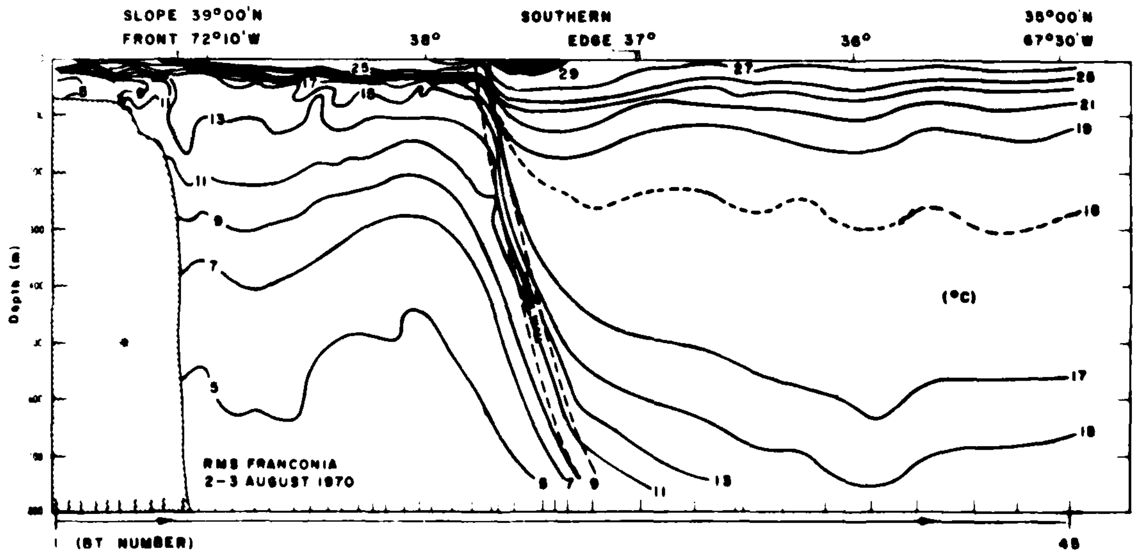


Figure 4 - Typical Summer Temperature Cross Section Between New York and Bermuda

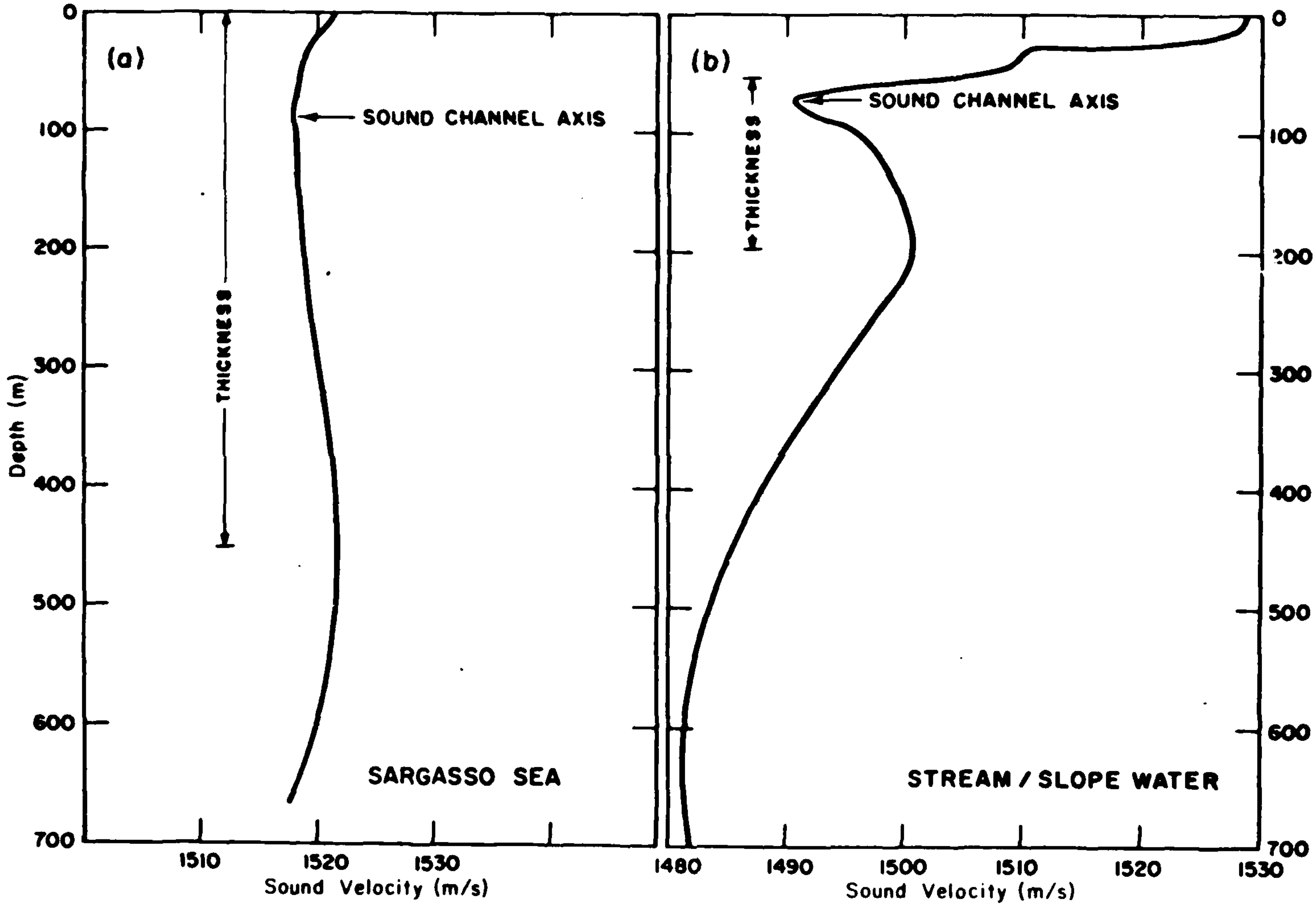


Figure 5 - Examples of Near-Surface Sound Channel

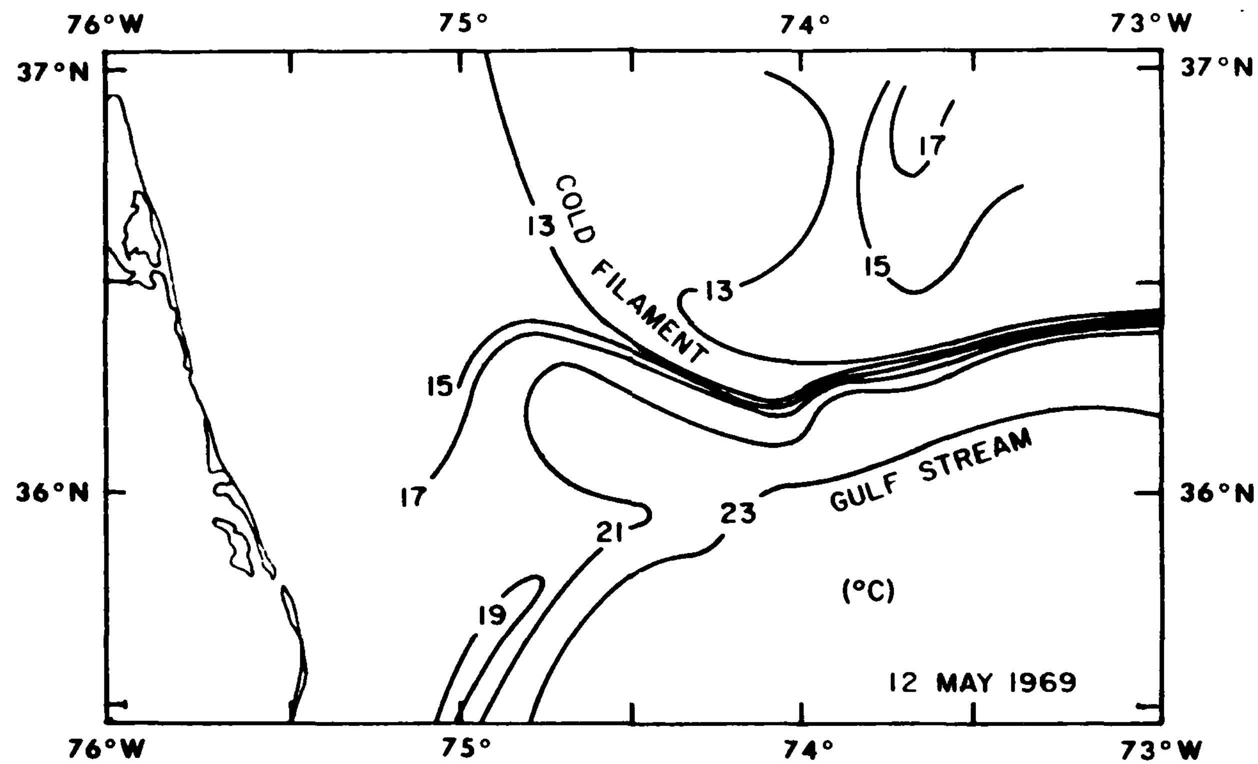


Figure 6 Entrainment of Cold Water by the Gulf Stream

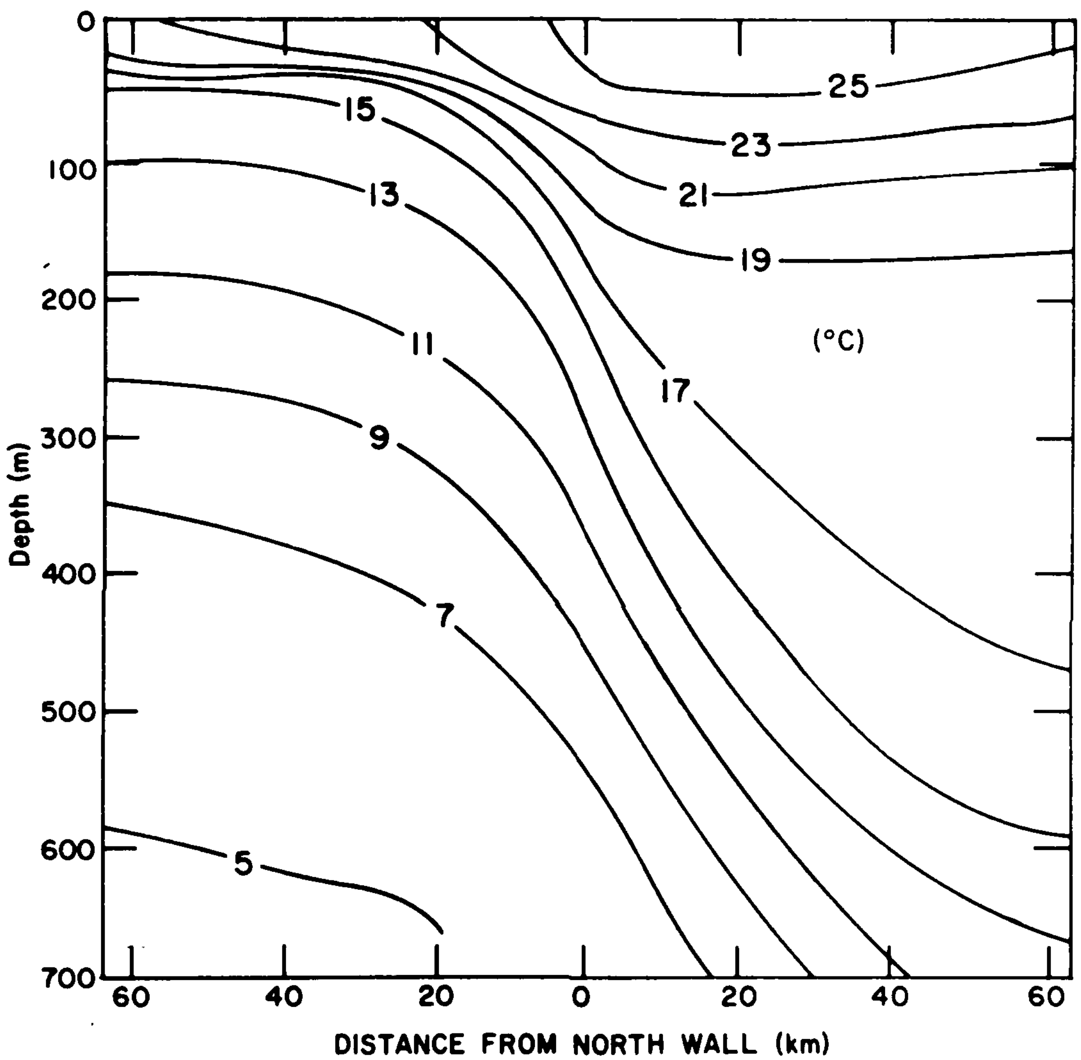


Figure 7 - Mean Thermal Structure of the North Wall

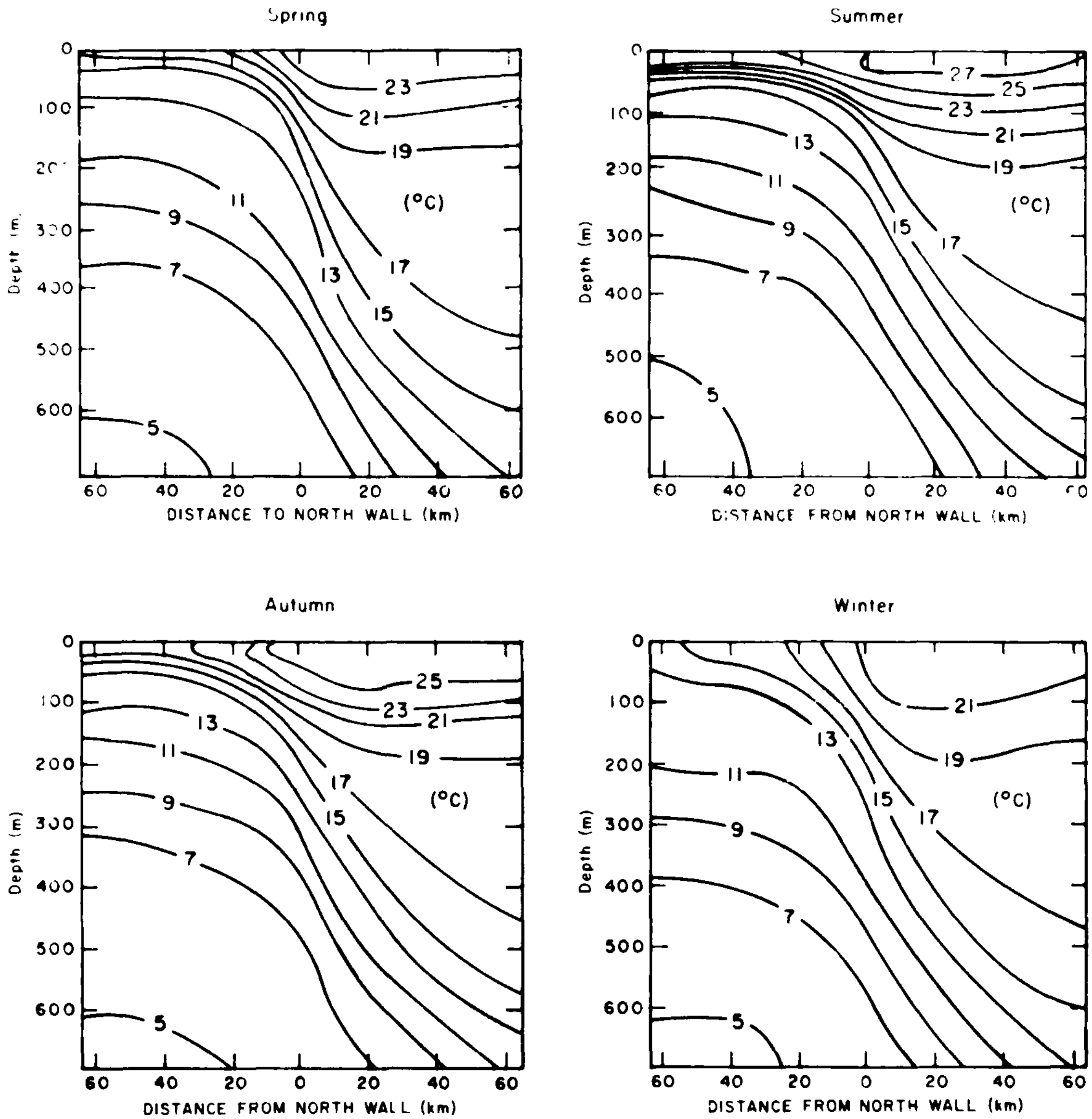


Figure 8 - Mean Seasonal Thermal Structures of the North Wall

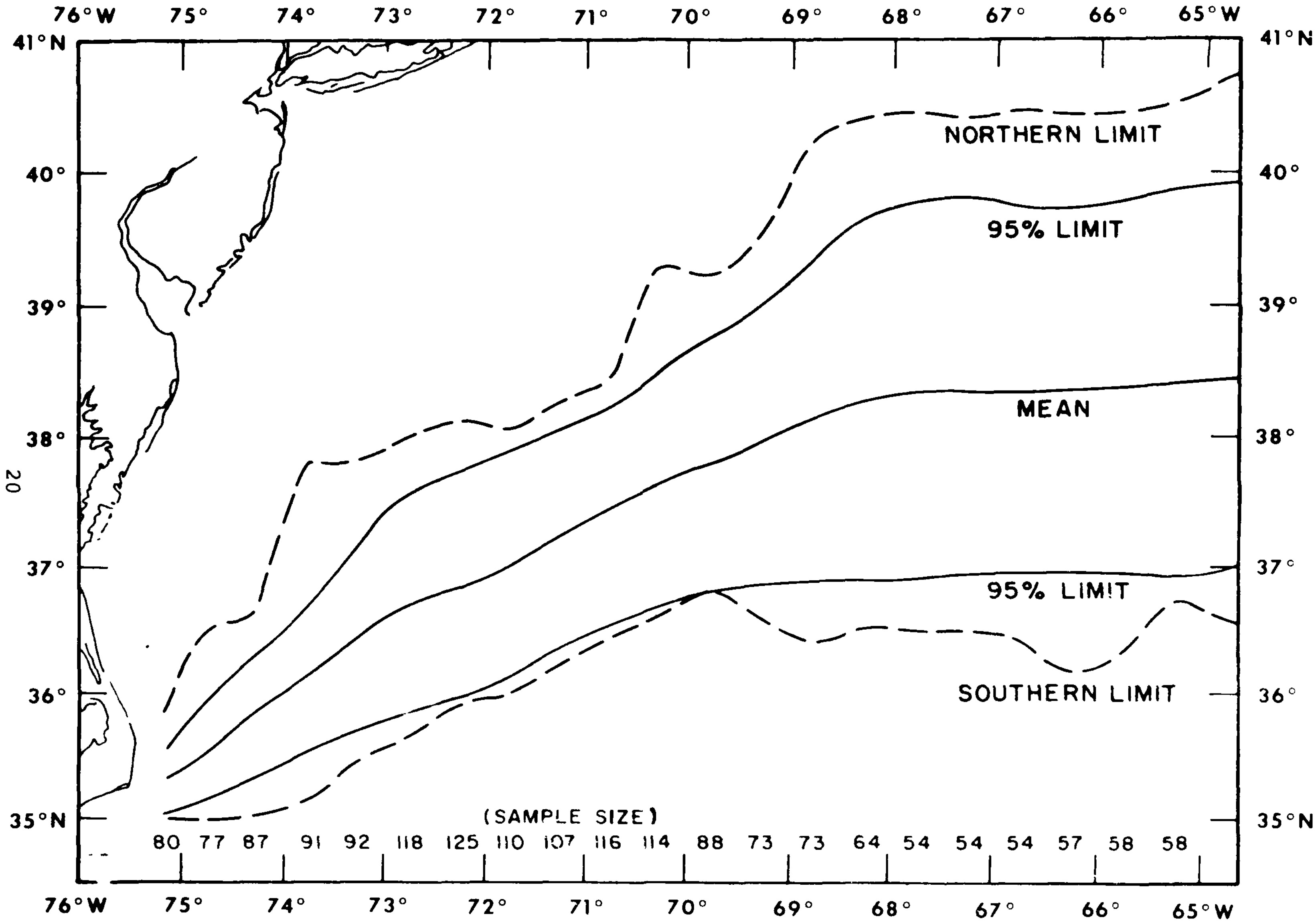


Figure 9 - Limits of the North Wall Positions

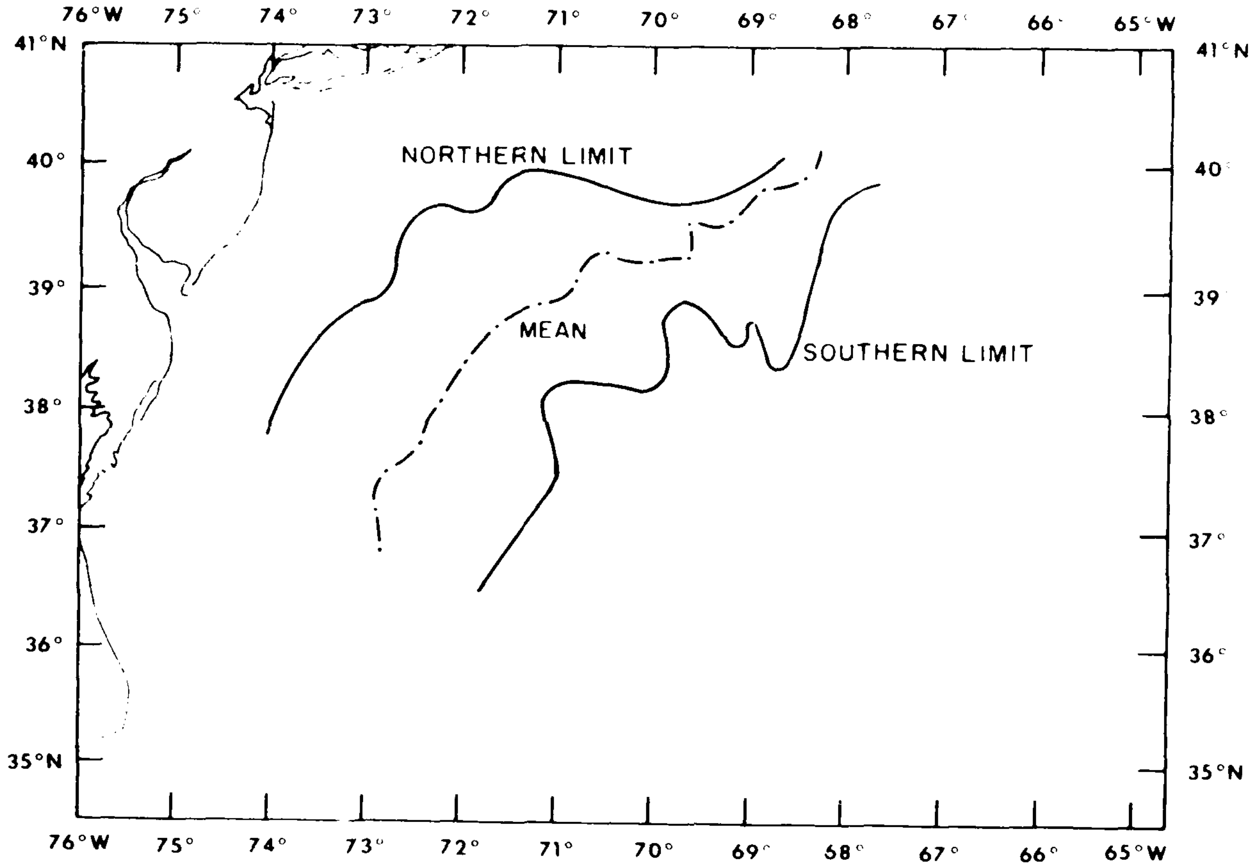


Figure 10 - Limits of Slope Front Positions

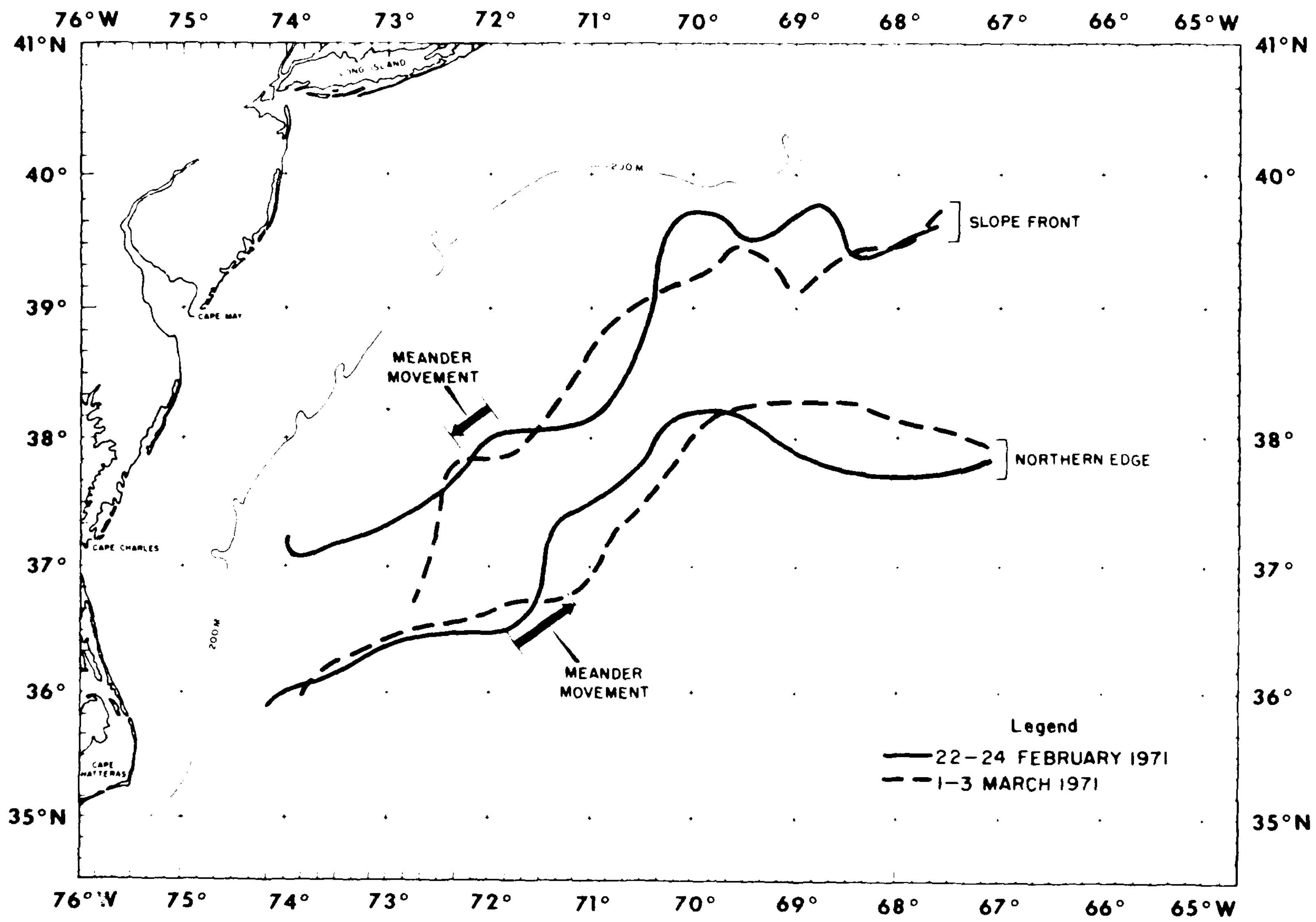


Figure 11 - Meander Movement of Slope Front and North Wall

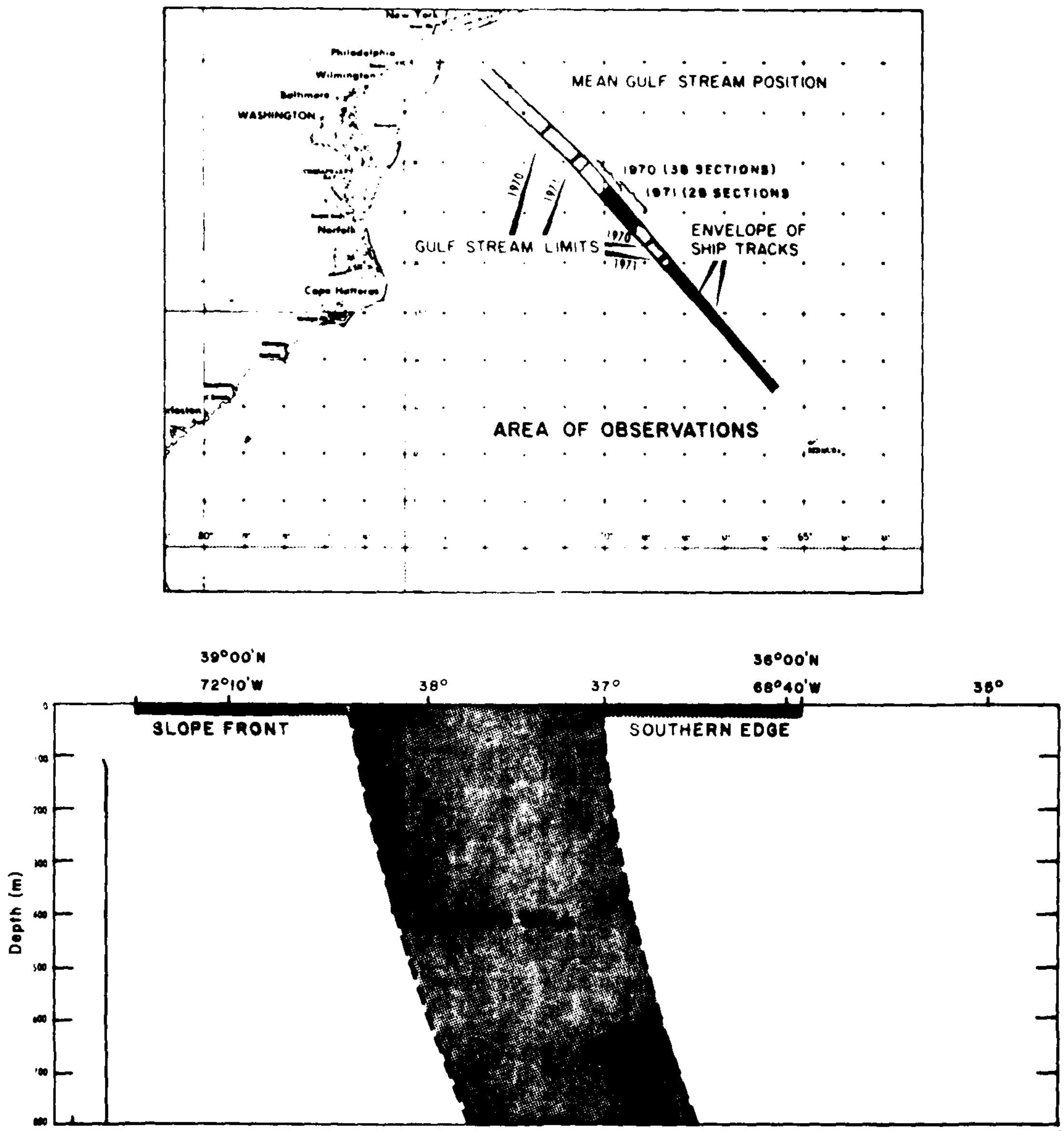


Figure 12 - Ship's Track and Mean Position and Range of the Fronts

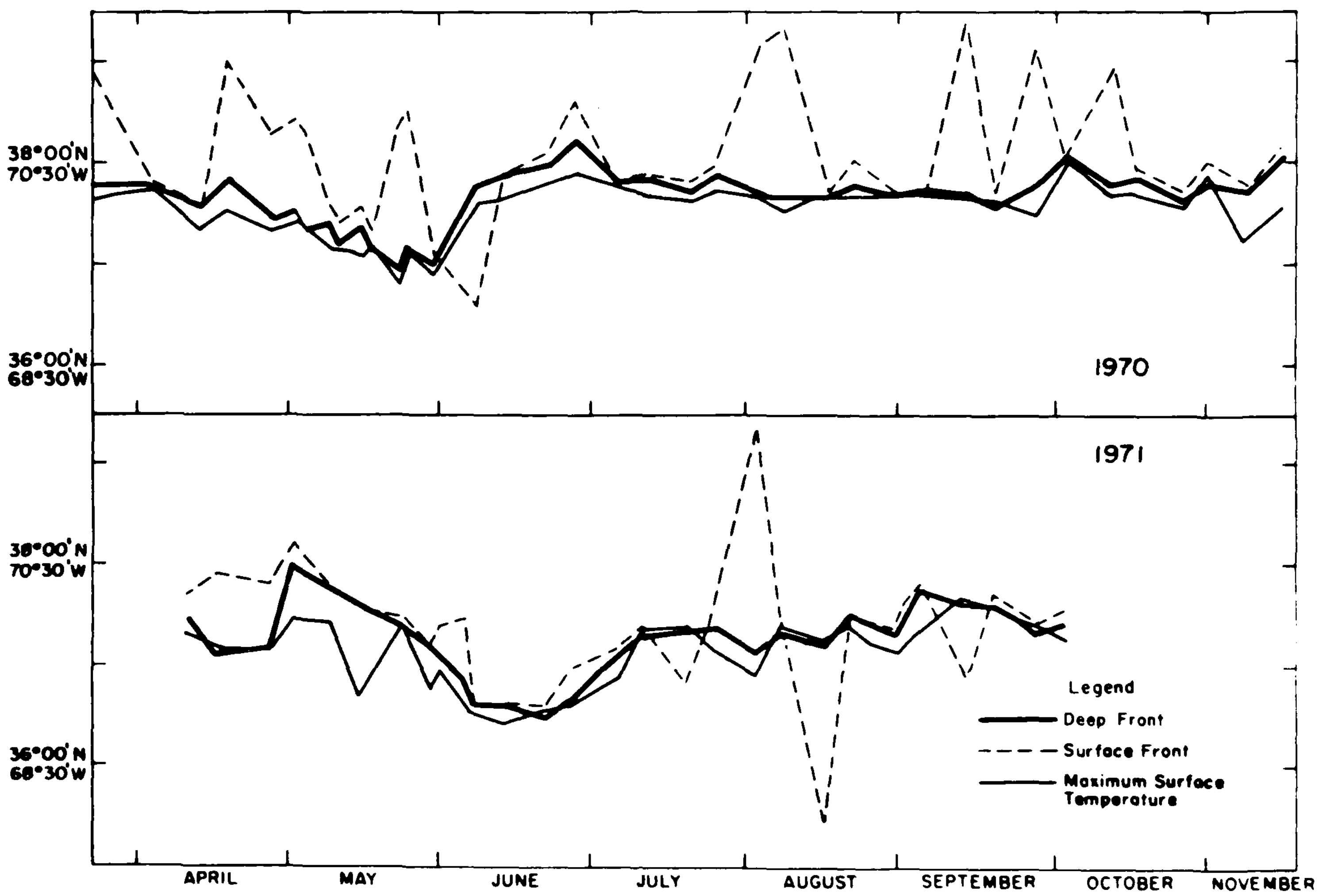
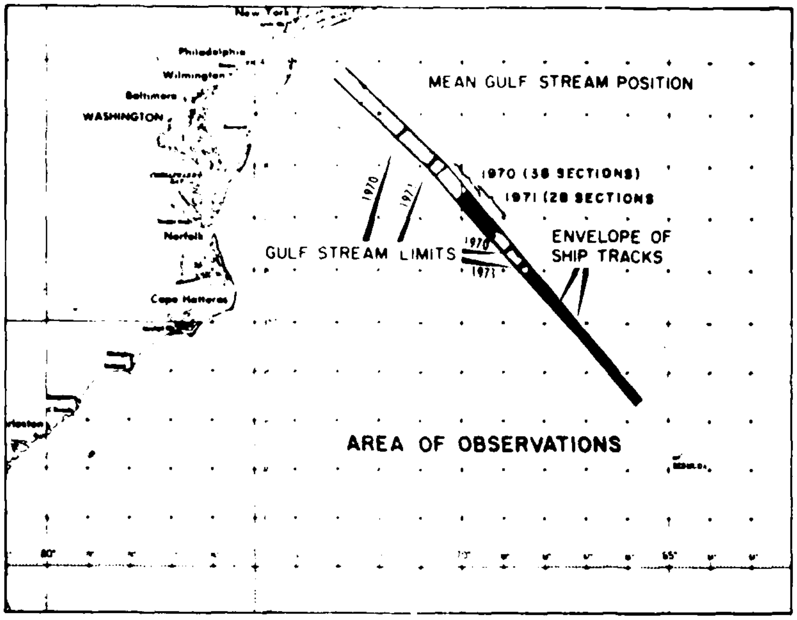


Figure 13 - Relative Position of the Maximum Surface Temperature and the Surface Front to the Deep Front



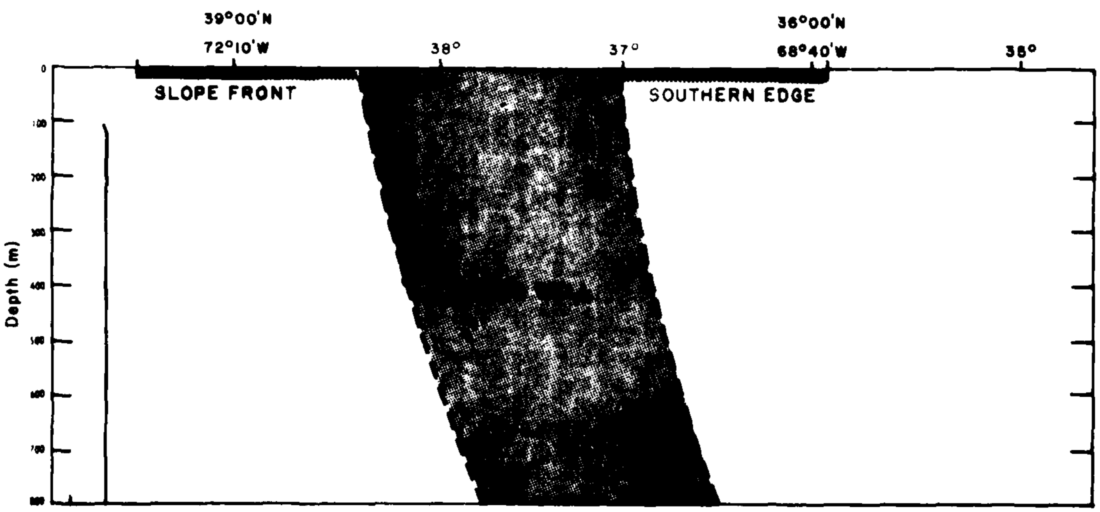


Figure 12 - Ship's Track and Mean Position and Range of the Fronts

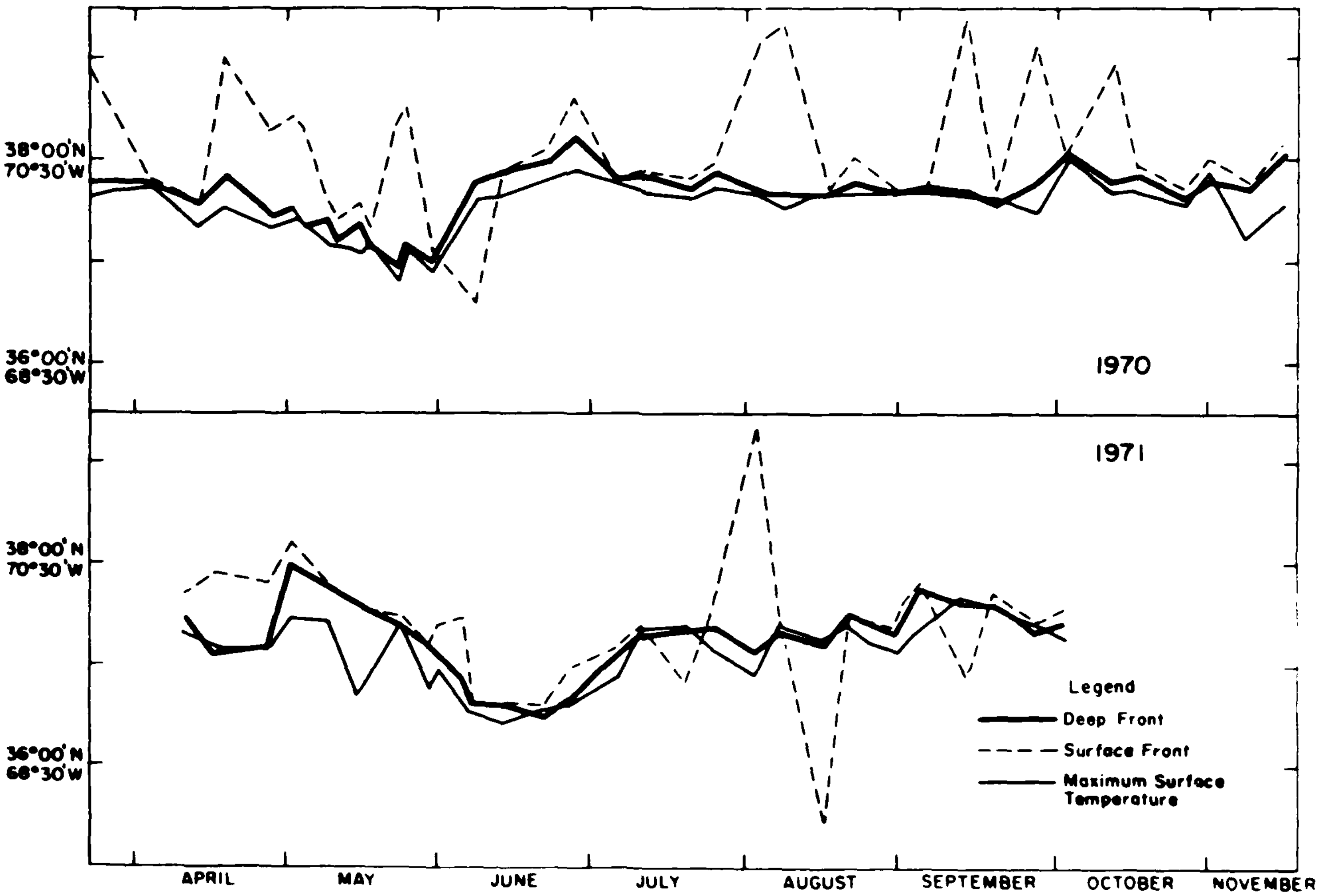


Figure 13 - Relative Position of the Maximum Surface Temperature and the Surface Front to the Deep Front

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Spatial variability and thermal characteristics of the Gulf Stream and the Slope Front are summarized to show the average or typical conditions. Thermally related parameters, such as sonic layer depths and sound channels, are summarized for each water mass separated by these fronts and subdivided by seasons. Results show that the thermal structure in the Gulf Stream region can be predicted, if the position of the Gulf Stream North Wall is known. In the absence of subsurface data, the North Wall...

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position can be estimated better from the maximum surface temperature than from the maximum surface thermal gradient.